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HYBRID (PVT) DOUBLE-PASS SYSTEM FOR AGRICULTURAL PRODUCTS: REVIEW

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ABSTRACT

The drying process plays a crucial role in post-harvest technology for the preservation of agricultural products. Due to the increasing cost of electricity and fossil fuels, application of sustainable solar energy for drying of various agricultural, meat and fisheries products has become a desirable alternative. It is not only economical but also reduces greenhouse gas emissions. Solar drying is a clean and hygienic way to process products according to national and international standards. The component analysis for designing a hybrid photovoltaic thermal double-pass system is covered in this review. The aim of this review was to gain an understanding of mixed-mode solar dryers for agricultural applications by investigating the influence of solar collection, thermal storage, photovoltaic panels, and control methods.

KEYWORDS: Solar Dryers, Solar Thermal Collectors, Thermal Energy Storage & Hybrid Photovoltaic Thermal Double-Pass System

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Original Article

1. INTRODUCTION

Solar drying is one of the oldest techniques of food preservation. It is the process of removing moisture from fruits, vegetables and other agricultural products using the sun, and it is beneficial because it limits decomposition caused by microorganisms such as enzymes and bacteria. In the past, the sun has been utilized by humans who removed moisture from food products, including meats, fruits, grains, and herbs (Nummer, 2002). The Food and Agriculture Organization of the United Nations (FAO) (Hlomendlini, 2019), estimates that food losses range between 30% and 40% in Africa, with South Africa contributing over 10 million tons of wasted food annually. These losses comprise 44 % fruit and vegetables, with the remaining 56 % being grains and meat. About 50 % of the food is lost during the post-harvesting phase. The FAO estimates that minimizing food waste globally would be enough to feed over 800 million people, hence the importance of developing better methods of food preservation. Of the various methods available to preserve agricultural products, solar drying is energy efficient and eco-friendly and can contribute to food preservation, ensuring that the quality of agricultural products is not compromised (Herringshaw, 2015).

The posed solution consists of a mixed-mode dryer system connected with a hybrid photovoltaic-thermal (PVT) double pass counter-flow system. A hybrid PVT combines a solar thermal collector and a photovoltaic panel (PV) into a single unit. While the thermal collector heats the working fluid (air) and increases thermal efficiency by up to 50%, it also draws heat away from the PV panel, increasing electrical efficiency by 15 % to 20 % (Abdul-Ganiyu et al., 2020). Flat-plate fin and tube collectors, evacuated tube collectors (ETCs), and parabolic trough thermal collector types, and PV panel types are investigated further in the text for appropriate application. Thermal

energy storage solutions, including sensible and latent heat systems, potentially improve operation time and heat transfer of drying systems (Elmeriah et al., 2018; Komolafe & Waheed, 2018). With power generation being limited to daylight hours, careful consideration of battery management and electronic control as well as insulation placement and properties aid in maximizing a system's thermal and food safety and efficiency with minimal environmental impact (Glavin & Hurley, 2006). This review serves to analyse the previously mentioned topics further with the hope of developing an appropriate, cost-effective, and environmentally ethical solution.

2. AGRICULTURAL PRODUCTS

2.1 Maize

According to Syngenta (n.d.), South Africa produces 10 million to 12 million tons of maize annually. Kaaya and Kyamuhangire (2010) note that correct preparation, drying, and safe storage of maize aids in preventing germination, insect damage, mold infection, and aflatoxin contamination. The moisture content of mature corn is approximately 32 %, which will reduce to between 22 % and 23 % moisture at harvest (North Dakota State University, n.d.). Safe moisture content for maize storage is 12 % to 14 %. Bare ground drying of dehusked whole cobs, with an ambient temperature of 28 °C, decreases the moisture content over five days from 24.8 % to 14.2 %. Drying in a biomass dryer reduces the moisture content from 24.8 % to 13.2 % over 6 hours, where temperatures vary between 28.1 °C and 52.4 °C (Kaaya &Kyamuhangire, 2010). This indicates that an increase in surrounding air temperature during drying (whether by renewable or non-renewable means) decreases the drying time of maize significantly.

2.2 Biltong

Li et al. (2019) found that biltong (beef jerky) is a highly popular food amongst mountaineers, sportspersons, and travellers, with FAO reports concluding that biltong consumption with respect to total meat consumption in developing countries increased from a modest average annual per capita consumption of 7 kg in 1960 to 18 kg in 2000 to a potential of 26 kg in 2030. With water accounting for 75 % of muscle weight in living tissue, and 65 % to 80 % in post-mortem tissue, the dehydration stage in the preparation of biltong is costly and power intensive. The popularity of natural dehydration has resulted in warm air drying through forced convection evolving as the most common dehydration mode, as the increase in fluid temperature and velocity of the air stream increases the heat and mass transfer rate. However, an experiment conducted by Sin-Woo et al. (2004) found that cold air drying produced a superior quality level of biltong compared to forced-convection hot air drying, which indicates that temperature levels reached by a hybrid dual mode solar dryer could produce subpar quality levels of biltong.

2.3 Chilies

Agricultural products can be contaminated by pests, dirt, rodents, and microorganisms during an open drying process. The losses due to contaminations can result in a 40 % to 60 % loss in a product's quantity. Pakhare and Salve (2004) researched the drying of chilies using a forced convection solar dryer. The drying rate of chillies was directly proportional to the variation in moisture content between the crop of choice to be dried and the equilibrium moisture content. The mass of red chili before and post solar drying was 30 kg and 8.75 kg, respectively. Drying of the red chilies took an average of 43 h by the solar drying system but took 91 h in open sun drying, with the same weather conditions. The initial and final moisture content of chilies from the solar dryer was 73 % and 14 %, respectively, and from the open sun-dried chilies was 73 % and 18 %, respectively.

2.4 Mangoes

Mango trees can be found in most parts of South Africa because mangoes can survive in different weather conditions. Mango trees can survive in areas with a very high annual rainfall and high temperatures (South Africa, Department of Agriculture, n.d.) Mangoes need to be preserved because of the dangers of quality being degraded by insect infestations, rodents, micro-organisms, dust, and animals. Dried mangoes contain high levels of several important vitamins and minerals, and are low in calories. Mangoes contain a small amount of calcium, pantothenic acid, and phosphorus. Mangoes are dried because they offer far more extraordinary properties than normal mangoes. Dried mangoes can boost the immune system and lower blood sugar levels. Akoy et al. (2020) reported that 100 kg of sliced mangoes were dried in 20 hours at an ambient temperature varying from 30 °C to 32 °C and 15 % relative humidity using a solar dryer. It was found that the moisture content of the sliced mangoes was 81.4 % initially and 10 % after the drying process. This indicates that the surrounding air temperature and relative humidity has an impact on drying time. Drying time can be decreased with high temperatures.

2.5 Moisture Content of Agricultural Products

Figure 1 provides evidence that the solar drying rate is more optimal using a solar dryer system compared to the open sun drying method.

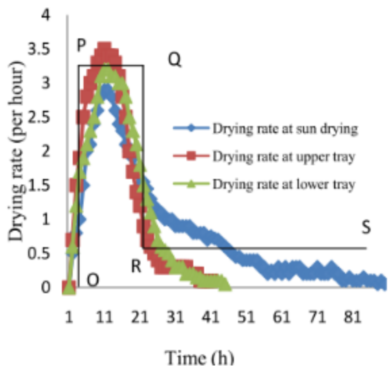


Figure 1: Drying Time of the Red Chili under Sun-Trying Conditions and Forced Solar Drying Conditions (Indicated by Upper and Lower Tray) (Pakhare & Salve, 2016).

An agricultural product's moisture content is expressed as a percentage of moisture based on wet weight (wet basis) or dry matter (drybasis).

$$M_w(wetbasis) = \frac{w-d}{w} \times 100 \quad (1)$$

$$M_d(drybasis) = \frac{w-d}{d} \times 100 \quad (2)$$

The moisture quantity to be removed is calculated using the equation:

$$M_r = \frac{Mp(Mi-Mf)}{(100-Mf)} \quad (3)$$

Where M_r = moisture to be removed (%), M_p = Sample weight (kg), M_i = Initial moisture content (%), M_f = Final moisture content (%).

The specific heat of chilies can be calculated by:

$$Cp = \frac{k}{\rho_b \alpha} \tag{4}$$

Where C_p is the specific heat (J/kg.K), k = thermal conductivity of chilies (W/m.K), ρ_bPb = bulk density of the chilies (kg/m^3), and α α = thermal diffusivity of chilies (m^2/s).

3. SOLAR THERMAL COLLECTORS

3.1 Evacuated Tube Collector (ETC)

An ETC is a non-concentrating solar collector using parallel rows of transparent glass tubes containing copper or aluminium fins. The first type is a sealed copper heat pipe ETC containing a small amount of alcohol (with all air extracted) running along an absorber plate. The vacuum causes the liquid to vaporize and condense at much lower temperatures within the heat pipe. Heat exchange to the working fluid (air or water) then occurs within the copper manifold (Hydro Solar, 2021). The second type is a direct flow, U-shape, piped ETC running within a glass tube where cold fluid flows in one end and hot fluid out the other. An absorber plate separates the in-flow and return pipes. In both cases, the glass tube's cylindrical shape causes the sun's incident rays to be perpendicular to the collectors. Therefore, the panel does not have to tilt and follow the sun (Alternative Energy Tutorials, 2021).

An energy performance study under Mediterranean climate conditions showed a flat-plate collector's annual solar yield to be 664 kWh/m^2 $664\ kWh/m^2$ with 49.4 % efficiency. In comparison, the heat pipe ETC produced 885 kWh/m^2$885\ kWh/m^2$over a year with 62 % efficiency (Maraj et al., 2019). ETCs are more efficient than flat plate solar collectors as they do not require direct sunlight and can operate by extracting heat from the air even on overcast days (Alternative Energy Tutorials, 2021). Glass tubes are manufactured from borosilicate or soda lime with high strength and temperature resistance. An absorptive coating also significantly reduces loss of heat (Hydro Solar, 2021). However, the vacuum may cause the tubes to reach high temperatures, causing cracking and overheating. Overheating is potentially worsened using air in the heat exchanger instead of water which is typically used as the working fluid. Finally, although more efficient, ETCs are significantly more costly than other solar collection methods (Alternative Energy Tutorials, 2021).

3.2 Flat Plate Solar Collectors

Solar collectors are devices that collect and concentrate solar radiation from the sun. Solar collectors are devices that convert solar energy into thermal energy. Flat plate solar collectors are mostly used to heat water and air for personal uses. (Hanania, 2018). There are different designs for solar collector plates namely the fin-type and the tube type. The fin-type is mostly used when air is the fluid medium while the tube type is used when water is the fluid medium. Flat plate collectors are a simple type of solar collectors since they are cost-effective in terms of purchasing. As shown in Fig. 2, ɑ flat plate collector loops the fluid through and heats it up. This occurs when radiation energy from the sun has been transformed into thermal energy through the collector (Berrow, 2018). Fig. 2 shows the flow of the fluid through the tube which is located between the glass glazing and the absorber plate.

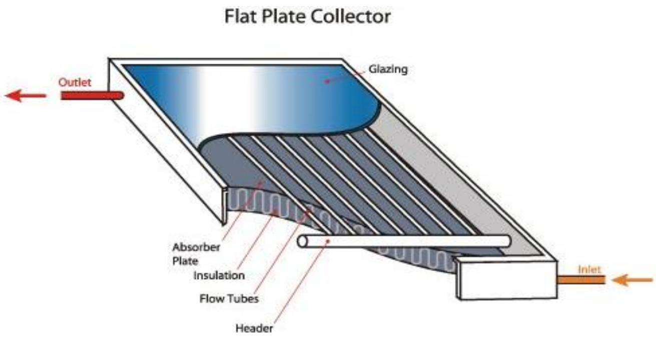


Figure 2: Flat Plate Collector (Abdullatif, 2020).

In a dual-pass solar collector, the working fluid flows through both sides of the double-pass collector. A dual-pass solar collector has a higher heat transfer rate from the absorber plate compared to the single-pass solar collector. Solar collector plates are usually made from metals due to their high conductivity. This plays a vital role when it comes to heat transfer. These metal plates are usually made from copper or aluminum, due to their good thermal conductivity properties (Abdullatif, 2020).

Table 1: Advantages and Disadvantages of Solar Collector Plates (Berrow, 2018)

Advantages	Disadvantages
Requires little maintenance	Mostly used to heat water only
Low cost	Performance is very low on cloudy days
No pollution and global warming effects	

Hegde et al. (2015) state that the performance of a solar collector is defined by the energy gains and losses. A thermal investigation is used to examine the heat gain as well as the thermal losses of the flow of air within the solar collector. This test analysis indicates that the top, sides, and bottom of the solar collector are exposed to heat losses; the temperature difference between the collector and the ambient temperature cause the thermal losses from the top, sides and bottom of the solar collector. The main idea of improving the system is to improve the solar collector, which can be done by increasing the solar sensitivity of the absorber. Thermal losses are one of the main problems that lead to less heat transfer and by minimizing thermal losses the performance of the system can thus be improved (Asme Digital Collection, n.d.).

3.3 Fin-Type Solar Collectors

Fins have been explored to improve the efficiency of solar collectors. Fins are an integral component of heat transfer systems and increase the surface area for absorption. The presence of fins enhance a PV panel's electrical efficiency by increasing the heat removal rate from the cells. Research conducted by Daliran and Ajabshirchi (2018) found that fins increase the absorber plate's roughness, consequently increasing the heat transfer coefficient by increasing the friction coefficient. The increase in heat transfer coefficient reduces the overall loss of heat and produces elevated outlet temperatures, which is beneficial for drying. They found that the attachment of fins increased collector efficiency from 61 % to 87 %. Kumar and Rosenlearned from their experiment that by using a fin area that provided surface extension, the cell temperature reduced from 82 °C to 66 °C, and vertical fins increased the heat transfer area to the air in the outlet channel of the double-pass system. The addition of fins at the rear surface of the absorber improves the thermal and electrical efficiencies.

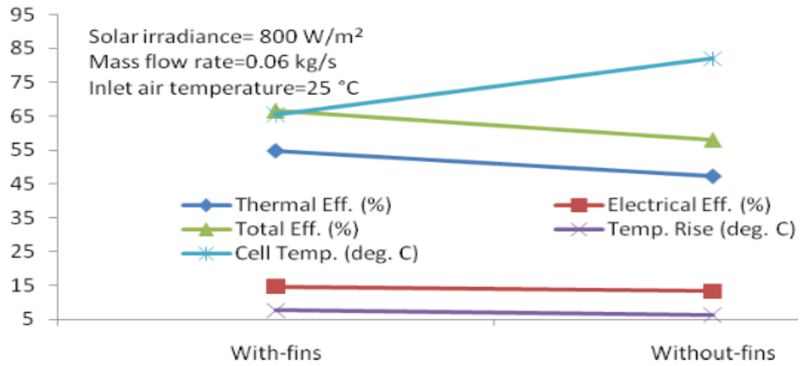
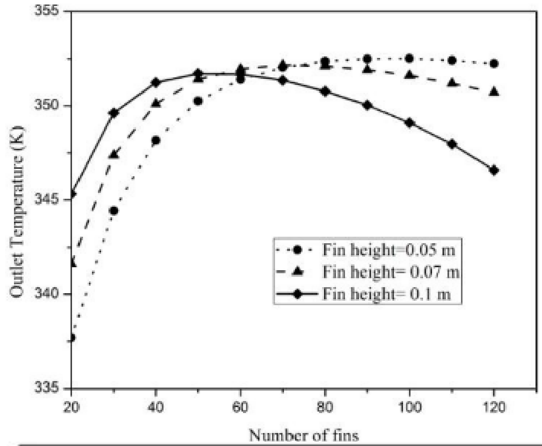


Figure 3: Comparison of Efficiencies, Air, and Cell Temperatures for a Solar PVT System, with and without Fins (Bhattacharyya et al., 2017).

Bhattacharyya et al. (2017) reported that the pressure drop and outlet air vent temperature of the double-pass system are parameters used to determine the optimum fin height, thickness, and quantity. Outlet air temperature increases and eventually decreases with the number of fins. On the other hand, pressure drop has an inverse relation to the quantity of fins.

Figure 4 and Figure 5 indicate an optimum number of fins and fin thickness, after which the fin effectiveness deteriorates.



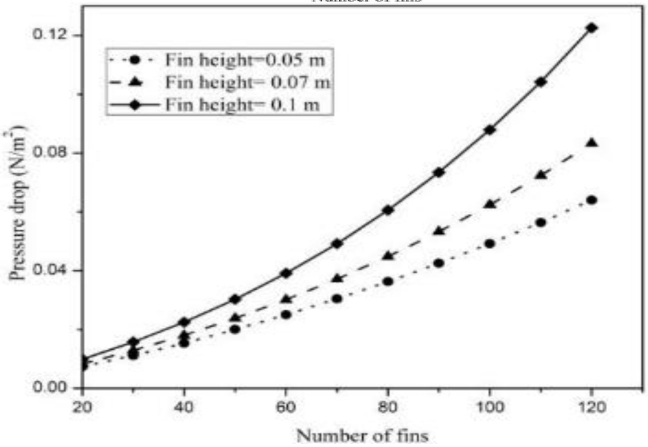


Figure 4: Variation of the outlet Vent Temperature with Number of Figure 5: Variation of Pressure Drop with the Number of Fins for a Fixed Fin Thickness and Mass Flow Rate (Fudholi et al., 2019) Fins for a Fixed Fin Thickness and Mass Flow Fate (Fudholi et al. 2019).

The double-pass finned system can be improved by having fins above and below the absorber, at the inlet and outlet channels. The fins at the outlet channel can be made from cut aluminium cans to reduce costs and aid recycling. The effectiveness of solar drying can be enhanced by combining a finned system with a parabolic collector. Fudholi et al. (2019) investigated several PVT systems and discovered that a compound parabolic collector (CPC) produced the highest thermal and electrical efficiency.

3.4 Parabolic Trough Solar Collectors

The parabolic trough collector is a mode of concentrated solar thermal energy production deriving its name from the trough-shaped collection of reflective elements responsible for the diversion of the heat energy from the sun's rays. The reflective elements provide the core basis of the functioning of the parabolic trough, and the diversion of light rays they are responsible for allows for the solar capacity of a large surface area to be concentrated upon a single heat receiver, an absorber tube (generally a specialized form of piping).

Reddy et al. (2013) state that the clever use of appropriate heat transfer fluids together with dynamic orientation of the trough geometry can allow for solar concentrations between 60 and 100, potentially reaching heat transfer fluid temperatures of 550 °C, at efficiencies of between 60 % to 80 %.

Research and computations compiled by Coccia et al. (2016) provide the basis for the calculation of the most optimal PTC orientation at a given co-ordinate set and time allowing for prime efficiency levels for all but a few daylight hours of a given day. They concluded further that the maximum achievable temperature of 450 °C for a parabolic trough was nearly six times greater than that of a flat plate collector at 80 °C.

Elashmawy (2020) concluded experimentally that a parabolic concentrating solar tracker (with sensible heat storage) produced an energy yield nine times greater than a conventional solar tracker with an increases of 27.33 % efficiencies.

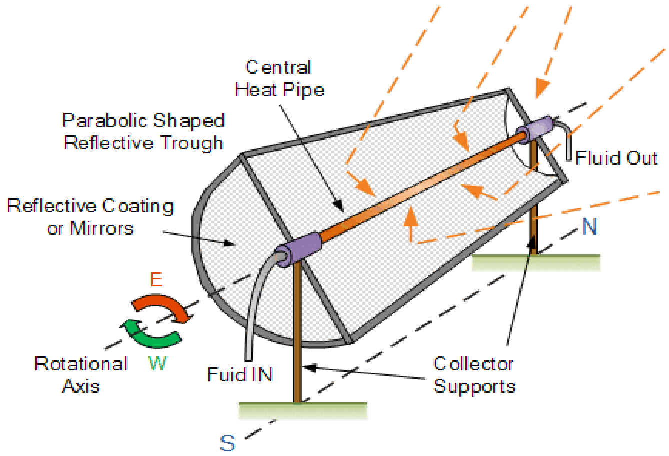


Figure 6: Principle Operation of a Parabolic Trough Solar Collector (Pakhare & Salve, 2011).

3.5 Hybrid Parabolic Trough and Finned Collector

The proposition of internally finned fluid vessels, essentially a hybrid design of a parabolic trough and finned collector, mathematically accounts for a greater Nusselt number, pressure losses, optimal thermal efficiency, receiver temperature, and heat transfer coefficient through the extended heat transfer surface area provided by the fins.

Research conducted by Fudholi et al. (2019) found that the use of compound parabolic concentrators in conjunction with PV/T technologies as well as internally finned piping provided for significant increases in efficiency, from 12 % to 70 % in the PV/T without the finned extensions, to 21 % to 83 % in the PV/T with the finned extensions, and thermal energy capture of the system of 15.7 % to 42.8 %.

4. THERMAL STORAGE SYSTEMS

A thermal energy storage system provides heat to the air flowing through the system when direct sunlight is not present. According to Pakhare and Salve (2011), the main heat storage systems include latent heat and sensible heat storage as well as thermochemical heat storage.

4.1 Latent Heat Storage – Packed-bed

Packed-bed thermal storage systems utilize rocks, concrete, gravel, or bricks which absorb and store thermal energy. As a potential aggregate, soapstone has a specific heat capacity of 1 J/gK (Tulikivi, 2021). During daylight hours, the material absorbs heat from collector-heated air and radiation from the sun. The packed-bed can be combined with a thermal collector or the drying chamber itself (Bennamoun, 2013). According to Bennamoun (2013), three sunshine days (an accumulated 27 hours) were needed to dry a product from 28.2% to 11.4% without rock-bed thermal storage. However, including a rock-bed, time was reduced to 2 sunshine days (18 accumulated hours) and 13 off-sunshine hours. Although less efficient compared to other storage methods, a packed bed is most cost-effective.

4.2 Latent Heat Storage – Phase Change Material (PCM)

Phase change material (PCM) combined in a shell and tube heat exchanger can also be utilized for heat storage. The PCM absorbs heat from the collector-heated air and changes phase from a liquid to a gas or from a solid to a liquid, thus retaining the heat. Pakhare and Salve (2011) observethat the addition of thermal heat storage using paraffin wax as the PCM, increased the drying cabinet temperature to between 6 °C to 9 °C higher than the surrounding temperature during a 6 h to 7 h off-sunshine period. The specific heat capacity of paraffin wax is between 2.14 J/gKto 2.9 J/gK (pgimpex.com, 2021). Elmeriah et al. (2018) emphasize that the correct design of shell diameter and tube length will maximize efficiency. Fig. 7shows how longer tube length increases outlet temperature and time for heat discharge.

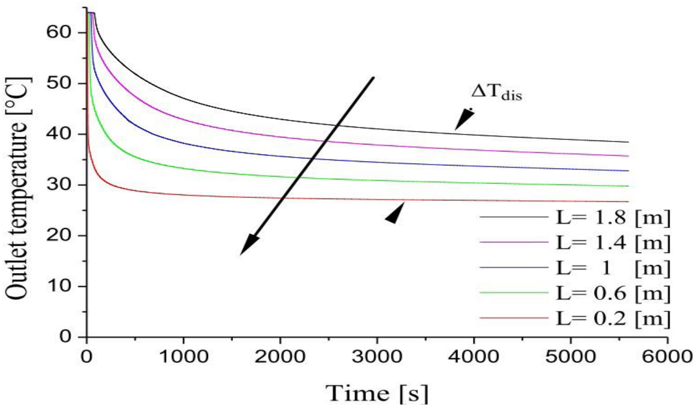


Figure 7: Graph Showing Effect of Tube Length on Discharging Cycle (Elmeriah et al. 2018).

4.3 Sensible Heat Storage

Sensible thermal energy storage (STES) is a mode of TES whereby the storage material temperature is influenced through

the storage of energy in that medium. The specific heat capacity of a material greatly influences its feasibility for use as a medium of sensible heat storage. Suitable materials for STES purposes have a high thermal storage capacity per unit volume and mass, high thermal conductivity, and high density, as well as many other factors. Common STES technologies in place as listed by Kalaiselvam and Parameshwaran (2014) are water storage tanks, rock beds, solar ponds, building thermal storage, and passive/active storage. Figure 8illustrates the material selection process for a good thermal storage medium.

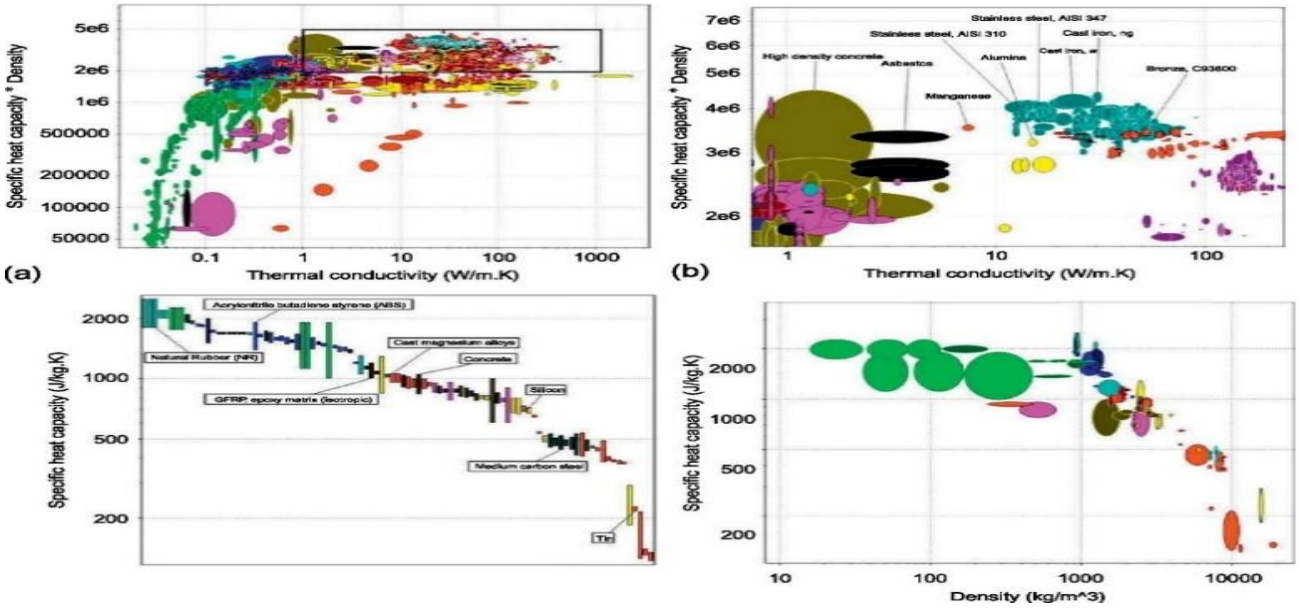


Figure 8: Material Selection for Sensible Heat Storage; a) Specific Heat Capacity*Density vs Thermal Conductivity (W/Mk), b) Extract from a), c) Specific Heat Capacity (J/kgK), d) Specific Heat Capacity (J/kgK) vs Density (kg/m3) (Luna et al., 2006).

Research conducted by Elashmawy (2020) studied the effect of adding a sensible heat storage system, using graphite as a medium, to a parabolic trough solar collector in conditions experienced in the Saudi Arabian desert. Their findings concluded that a sensible heat storage medium of just 3 kg of gravel produced increases in thermal efficiencies and yield by 13.89 % and 14.18 %, respectively. Further research by Kalairasi et al. (2020) surveyed the comparison in performance between a solar air heater with and without sensible heat storage in Mumbai, India. Their results were conclusive that the solar air heater with a storage medium (Therminol-55) provided a sharper increase in efficiency of 15 % to 20 % while further allowing for a consistent output temperature even after the lapse of the strongest sunray periods of the day. Similar experimentation by Luna et al. (2006) used water as a sensible storage medium in a solar kiln dryer, with water proving ideal due to availability, cost, and thermophysical properties. Comparing the system with and without sensible storage, they found that the system with the storage system exhibited a 30 % decrease in drying time.

The advantages of sensible thermal storage medium as listed by Kalaiselvam and Parameshwaran (2014) lie in their environmental friendliness, simplicity, and reliability, whereas their disadvantages stem from their low energy density, subsequent large volumes required, self-discharging loss issues, high costs, and geological constraints. As such, they are found at present only at large-scale demonstration plants.

4. 4 Thermochemical Energy Storage

Thermochemical energy storage systems utilize chemical reaction principles viz. the reversible chemical reactions that are

experienced through the interaction between two reactive elements. Heat and energy applied to these reactive elements and the subsequent disbanding of intermolecular bonding allows the separation of the elements into further individual reactants, thereby allowing the storage of heat energy. The stored energy can be discharged as required through the recombination of the aforementioned reactants, subsequently providing the heating energy required. The principal formulae upon which these reactions occur are as given (Kalaiselvam and Parameshwaran, 2014):

$$C_1C_2 + Heat\ input = C_1 + C_2 \tag{5}$$

Thermochemical energy storage falls into the categories of open adsorption, closed adsorption, closed absorption, solid/gas thermochemical, and thermochemical accumulator energy storage. Potential compounds for these storage methods are magnesium sulfate, silicon oxide, and iron carbonate, with energy storage densities of 2.8 GJ/m^3, 37.9 GJ/m^3, and 2.6 GJ/m^3 respectively (Kalaiselvam and Parameshwaran, 2014).

The ZAE Bayern company in Germany (Kerskes, 2006) has developed an open adsorption system aimed at providing a heating buffer capable of storing 1 300 kWh for 14 h of operating time daily. This system makes use of heat energy to perform the desorption reaction during off-peak hours and then releases heat energy through the adsorption reaction during night hours. The storage compound Zeolite 13X used is capable of a storage density for heating or cooling loads of 124 kWh/m^3 and 100 kWh/m^3 respectively with COPs of 0.9 and 0.8 respectively.

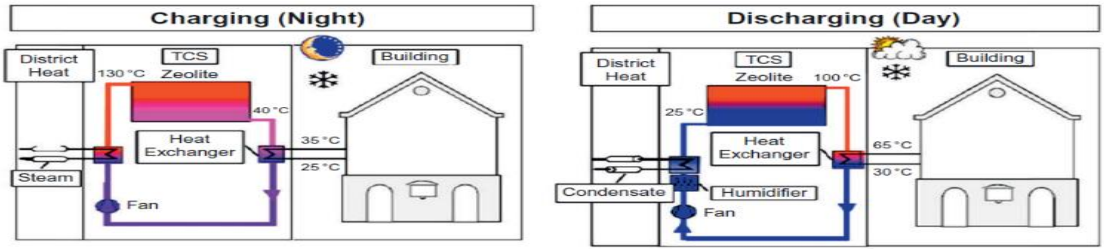


Figure 9: Open Adsorption System Developed by ZAE Bayern (Chopra and Durra, 2004).

The advantages of thermochemical storage mediums as listed by Kalaiselvam and Parameshwaran (2014) lie in their high energy density, compactness, and negligible losses. Their disadvantages stem from their poor heat and mass transfer properties in high-density conditions, uncertain cyclability, and high costs. For these reasons, they are at present mostly used in laboratory prototypes.

5. SOLAR PANEL VARIANTS

5.1 Thin-Film Solar Panels

Thin-film solar cells are used in minor electronics, watches, and pocket calculators. The panels comprise a single or several layers of photovoltaic materials laid on a substrate. Research gathered by Lee and Ebong (2017) found that thin-film panel efficiency range was 9.5 % to 18.6 %. The advantages and disadvantages of thin-film panels are as follows:

Advantages

- Thin-film panels are lightweight.
- The energy payback period (the period in which the electricity generated by the panel is equivalent to the energy needed to produce the panel) is shorter for thin-film panels than crystalline panels.

- Generally cheaper than crystalline panels.
- Disadvantages:
- Subject to light-induced degradation (due to different temperature coefficients), resulting in a decrease in output efficiencies.
- Not widely available due to manufacturing constraints and reduced solar cells material availability.
- Cadmium thin-film cells are toxic to the environment (Chopra et al., 2004; Lee and Ebong, 2017).

5.2 Polycrystalline Solar Panels

Polycrystalline solar panels consist of many crystals of silicon in a single PV cell. Each PV cell contains silicon crystals which enable it to function as a semiconductor device (The Economic Times, 2019). When the photon from sunlight hits the polycrystalline solar panels, they drop on the PN junction. This junction is positioned between N-type and P-type materials. This initiates energy variations in the electrons which enhance them to drift as an electric current. This then triggers the P-type material to be deficient in electrons whereas the N-type material has an abundance of electrons. The process of how sunlight radiation causes the movement of electrons in a PV panel is illustrated in figure. 10.

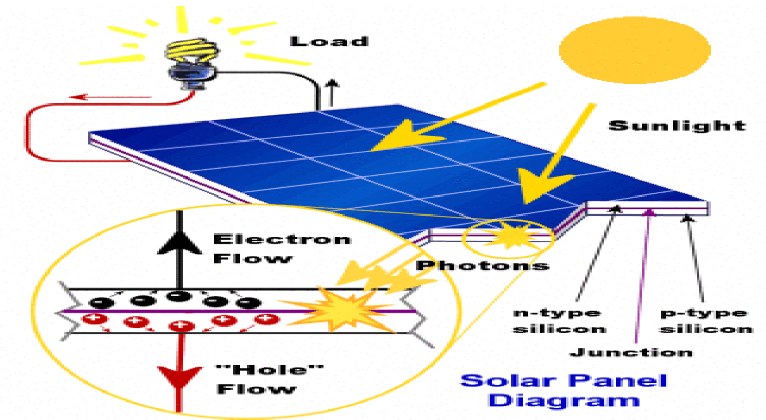


Figure 10: Illustration of Working Principle of Solar Panels (Faruqi et al., 2019).

An energy performance analysis under Kosovo climate conditions was conducted during December 2014 and November 2015 with a polycrystalline silicon module with 2.16 KWP capacity compared to a monocrystalline silicon module with a 1.76 KWP capacity. This analysis proved that monocrystalline PV modules displayed a higher performance compared to polycrystalline PV modules. Electricity production after analysis proved that monocrystalline produced 1 328 KWH/KWp whereas polycrystalline produced 1 286 KWH/KWp. This analysis shows that monocrystalline produces 42 KWH/KWp more than polycrystalline when tested in similar climatic conditions (Komoni et al., 2018).

The advantages and disadvantages of polycrystalline solar panels are listed in table 2.

Table 2: Advantages and Disadvantages of Polycrystalline PV Panels (The Economic Times,2019)

Advantages	Disadvantages
Environmentally friendly	Has a lower purity of silicon and less uniform look
Silicon is not wasted during the manufacturing process	Low efficiency
Heat tolerance is low	Less space-efficient
Very cheap and easy to manufacture	Requires larger surface areas

5.3 Monocrystalline Solar Panels

Monocrystalline PV panels are made using silicon wafers. The panel uses single-crystal silicon which enables the electrons sufficient space for movement thus providing better electricity flow (Solar Magazine, 2020). Monocrystalline PV panels convert sunlight energy into electricity. The single cell composed of crystals will allow the flow of electricity. Fig. 11 shows the efficiencies of monocrystalline and polycrystalline and various temperatures. From Fig. 11 it is evident that polycrystalline PV panels are more efficient than monocrystalline PV panels. Faruqi et al. (2019) reported that the addition of reflectors on monocrystalline PV panels produces far more current compared to ɑ reflector-free panel. It was also observed that current production was at its peak when solar radiation rises. The advantages and disadvantages of monocrystalline solar panels are listed in Table 3.

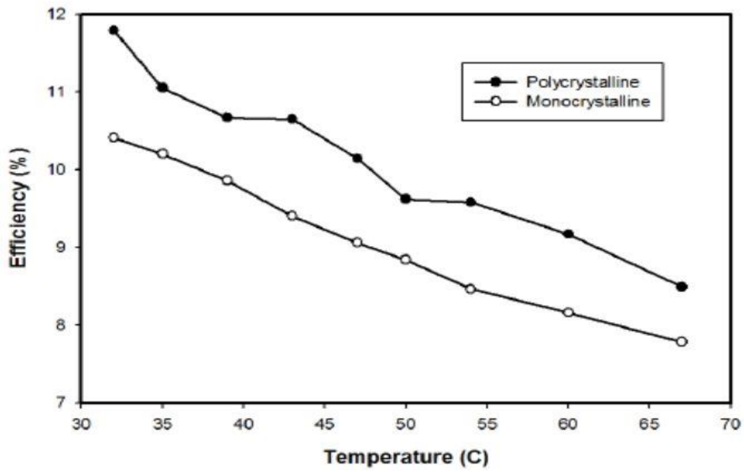


Figure 11: Temperature vs Efficiency between Poly- and Mono -PV Panel (Poulek, 1994).

Table 3: Advantages and Disadvantages of Monocrystalline PV Panels

Advantages	Disadvantages
Efficiency is high as it ranges from 15 % to 20 %	Very expensive
Require less space	Lot of material waste during manufacturing process
Performance is better in cloudy areas making them useful when sunlight levels are low	Performance varies when temperature increases

5.4 Comparison of Solar Panel Variants

Low coefficient of absorption, strength, unreliability, low efficiency, and scarcity of thin-film panels makes it an undependable panel of choice. Furthermore, thin-film panels have a lifespan of 20 years compared to the 25-year lifespan of monocrystalline and polycrystalline panels (Imamzai et al., 2011). The same number of photovoltaic modules, monocrystalline and polycrystalline panels have higher average efficiencies. Furthermore, the strength and reliability of monocrystalline/polycrystalline panels are not compromised (Ghazali M et al., 2012).

Figure 12 reveals that between 2006 and 2019, polycrystalline panel efficiency has risen at a higher rate

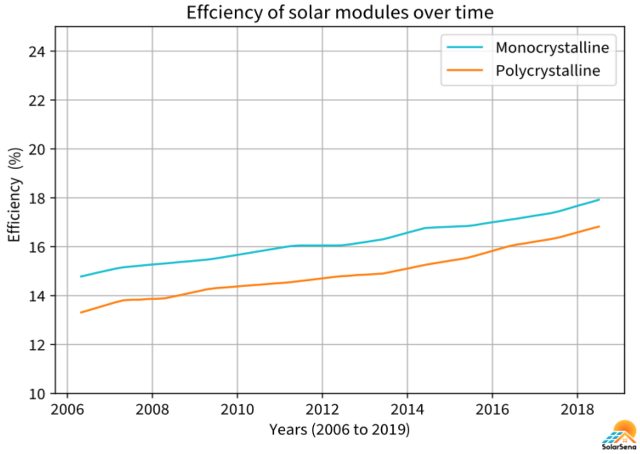


Figure 12: Comparison between Monocrystalline and Polycrystalline Panels (Hyperphysics.phy-astr.gsu.edu, n.d.)

Monocrystalline panels are more costly than polycrystalline panels. However, in response to demand, monocrystalline panels are more affordable in emerging markets (SolarSena, 2021).

The recommended panel in terms of efficiency and mechanical properties is, in descending order, monocrystalline, polycrystalline, and, lastly, thin-film panels. However, the polycrystalline panel is a cost-efficient option without compromising much of the desired efficiencies.

6. SOLAR TRACKING

Solar trackers follow the sun's path to optimize the efficiency and energy obtained from a photovoltaic panel. Solar tracking mechanisms are classified according to their drive types, namely, passive trackers and active trackers.

6.1 Passive Trackers

Passive trackers use the sun's thermal energy to induce imbalance, thus causing movement of the tracker. These trackers are based on thermal expansion and can be manufactured from shape memory alloys or low boiling point compressed gas fluid. A shape memory alloy (SMA) passive tracker actuator was designed by Poulek (1994). The tracker deformed at low temperatures and actuated to its initial form when subjected to heat above the transformation temperature. The study proved that this SMA tracker increased efficiency by 2 %. However, passive trackers fail to provide high efficiencies at low temperatures (Sumathi et al., 2017).

A novel investigation of using bimetallic strips/springs as passive solar trackers is being investigated (Zhu et al., 2020). The bimetallic strip works by affixing metals with different thermal expansion coefficients to produce practical devices for quantifying and detecting temperature changes.

A helix spring as illustrated in Fig. 13 is used to measure the temperature, and the exposed end of the helical spring is attached to the pointer, which deflects as the temperature varies (HyperPhysics, n.d.).

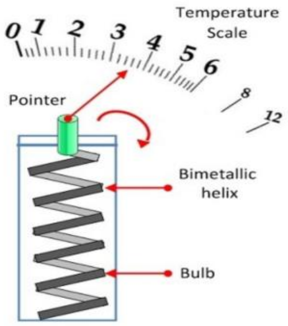


Figure 13: Helical Bimetallic Spring (Ye et al., 2019).

6.2 Active Trackers

Active trackers are widely commercially available and have established a reputation in the market. These tracking mechanisms are costly as they use motors and gears to manoeuvre the tracker. The motors are fed signals by the control system, indicating the magnitude and direction to perform the tracking manoeuvre. These trackers are more accurate in comparison to passive trackers. However, they consume excessive energy since they need to be powered. Nevertheless, active trackers produce elevated efficiency enhancements in comparison to passive trackers (Sumathi et al., 2017).

6.2.1 Single-Axis Active Tracker System

A single-axis tracker provides a single degree of freedom. Single-axis systems are categorized into north-south (NS) and east-west (EW) axis tracking. Studies were conducted by Chang (2009) to determine the performance of the single-axis panel configurations. The efficiency enhancement obtained by the NS tracker was higher than the EW tracker. A compound parabolic reflector can be used with the single-axis tracker to optimize the performance (Grass et al., 2004).

6.2.2 Dual-Axis active Tracker System

The dual-axis system contains two degrees of freedom which are perpendicular to each other and perform as axes of rotation. This system produces high precision compared to the single-axis system, thus providing a higher increase in efficiency. However, dual-axis systems are complex and therefore expensive.

Figure 14 displays the results obtained from the research conducted by Mousazadeh et al. (2009) in determining the effects of a fixed versus tracking system (dual-axis). The energy obtained by the tracking system was elevated in comparison to the fixed design for the same temperature. Incorporating a solar tracking system in a project benefits the electrical and thermal efficiency.

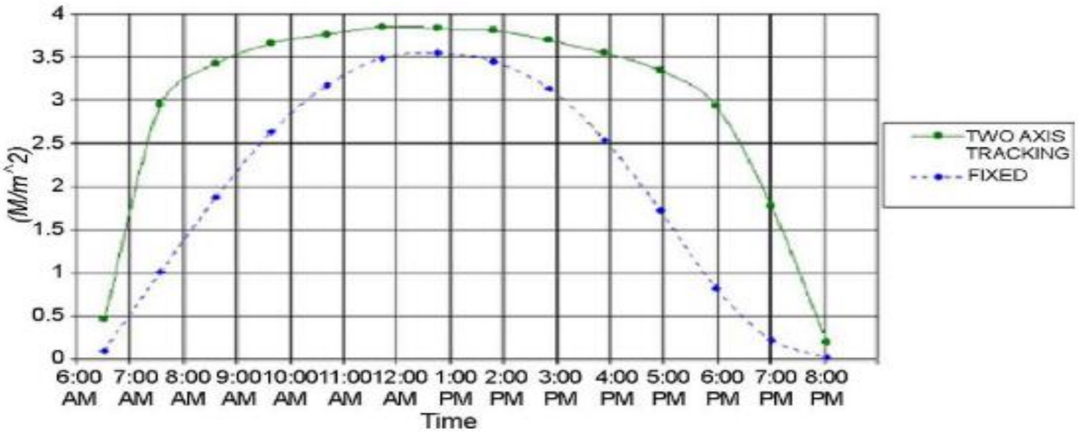


Figure 14: Fixed vs Tracking System Energy Gain (Behabtu et al., 2020).

7. TYPES OF FANS

Fans are devices with rotating blades that move air for cooling. There are four types of fans, axial fans, diagonal fans, centrifugal fans, and tangential fans. These fans each have different abilities which are suited for different purposes.

7.1 Axial Fans

In this type of fan, the airflow is directly in an axial direction since the airflow is directed parallel to the axis of rotation which is aided by an impeller. Axial fans can use low power input that increases back pressure which thus causes free air delivery at zero static pressure. Axial fans mostly have an electrical motor which is mounted in the fan hub, an arrangement which is space-saving due to the compact design. Axial fans are mostly commonly used for cooling electronic equipment. According to Ye et al. (2019)] a performance analysis was simulated between an axial fan based on a blade with or without skewing. The simulated results showed that total pressure increased by 3 % and efficiency increased by 0.2 %. Analysis showed that an axial fan with a skewed blade has a greater efficiency that a normal blade fan.

7.2 Diagonal Fans

Diagonal fans have a housing that is in a conical shape which causes the air to be pressurized. This is acquired since the intake air is axial, whereas the exhaust air is diagonal. High efficiency is acquired in a diagonal fan since performance is characterized by delivery of medium volume flow at medium pressures. A diagonal fan can operate at high pressure whilst enhancing low operating noise. Typical applications include air conditioning units where noise and high efficiency are critical.

7.3 Centrifugal Fans

Centrifugal fans are widely used in circumstances where the exhaust air must be deflected in a direction 90°° from the inlet flow. Centrifugal fans have a steep pressure characteristic developing higher pressure with a lower rate. These types of fans are mostly seen in particulate or odour filtration applications, or in fan coils where a high-volume is required in a restricted space envelope (double inlet blower) (FanManDan, n.d.).

7.4 Tangential Fans

In tangential fans air flows through the roller-shaped impellers twice in the radial direction. Air flows into the intake area from the outside and through the outflow area from the inside to the outlet. Tangential fans are mostly used to produce a

wide airflow distribution through devices. Tangential fans produce a wide laminar flow at high velocities. This type of fan is widely used in shop doorways.

8. BATTERY STORAGE AND MANAGEMENT

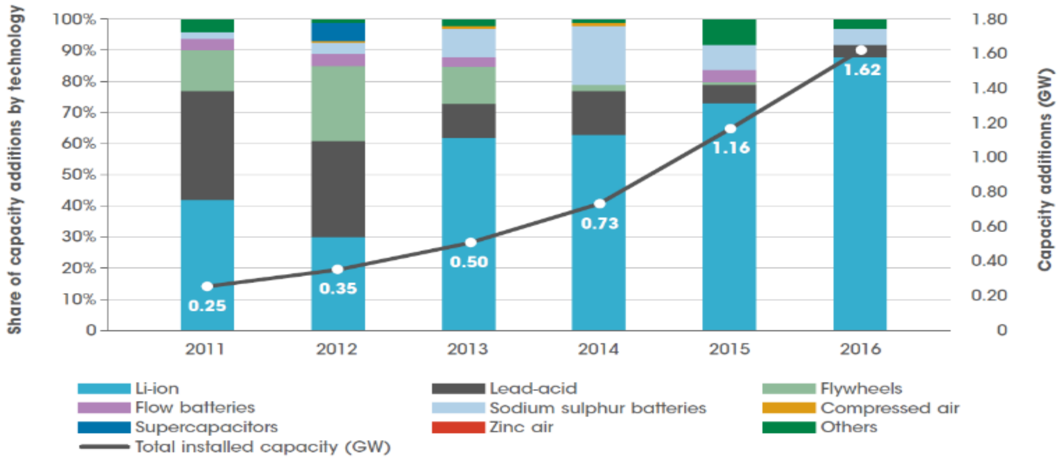
8.1 Lead Acid Batteries

Glavin and Hurley (2006) list the lead acid battery as one of the most used deep-cycle batteries in solar storage applications. Electrochemical reactions occurring at the anode and cathode have a charge state where lead (Pb) and lead dioxide PbO_2(PbO_2) combine with an acid electrolyte. During discharge, both Pb and PbO_2 PbO_2 react forming lead sulphate $PbSO_4$($PbSO_4$). Lead acid batteries have a 2000 to 2500 cycle lifespan over 5 years to 15 years (Akinyele et al., 2017). Its main attraction compared to other battery technologies, is affordability and its ability to smooth renewable energy output. This makes it a feasible option for use during off-sunlight hours for a solar dryer (Behabtu et al. 2020). Disadvantages include improper use, which accelerates toxin production, negatively impacting the environment (Akinyele et al. 2017).

8.2 Lithium-Ion Batteries

Lithium-ion batteries, although more expensive, are emerging as the first choice for electrochemical storage solutions. While charging, lithium ions move from the cathode (usually lithium metal oxide based such as $LiMO_2$$LiMO_2$) to a carbon-graphite-based anode. Here they recombine, forming lithium atoms, and during discharge, the reverse reaction occurs. The cycle life of lithium-ion batteries is 10 000 cycles – nearly four times greater than lead acid batteries (Akinyele et al. 2017).

Figure 15 shows the increase in lithium-ion battery capacity development globally compared with other electrical storage solutions (including lead acid batteries). The International Renewable Energy Agency (2019) credits the price decrease in lithium-ion technology, allowing for greater production. However, the cost is still much more compared to lead acid batteries.



Note: GW = gigawatt
Source: IEA (2018); Sandia Corporation (2018)

Figure 15: Graph Showing Share of Capacity Additions by Different Battery Technologies Globally from 2011-2016 (International Renewable Energy Agency).

8.3 Battery Management

Battery storage within a micro-grid system supplies power during off-sunlight hours. For a solar dryer, this, with adequate thermal storage, can significantly shorten the drying time of agricultural products as fans and controllers can operate during off-sunlight hours. To preserve the battery lifespan, Akinyele et al. (2017) suggest a depth of discharge (DoD) of 50 % for an off-grid PV system with lead acid batteries to maximize the number of life cycles. Glavin and Hurley (2006) also propose using a dual battery storage arrangement which includes a "working battery" and "storage battery". Implementing a battery management system or solar regulator controller allows the voltage to be kept constant, thus optimizing battery life.

9. INVERTERS

Inverters change direct current (DC) produced by solar panels and stored in batteries into alternating current (AC). Newly innovated "smart-inverters" monitor and control generation while communicating with the grid (Mallwitz & Engel, 2011). The two types of inverters for applications in the range of 1 KW to 100 KW are string and hybrid solar inverters as well as microinverters.

9.1 String Inverters

String inverters can accommodate more than one PV panel where panels are connected in series to the inverter. A drawback of string inverters is that the system's efficiency is compromised and decreases if one PV panel within the series is not performing or is "shaded" due to power optimization occurring at string level and not panel level. However, they are more cost-effective since multiple PV panels can be controlled using a single-string inverter (Sendy, 2020).

9.2 Microinverters

Microinverters optimize power collected by each panel as the inverter is connected directly to the panel itself. Unlike the string inverter, the microinverter is not affected by shading or tilt differences between panels and is, therefore, more efficient in comparison. Regarding both string and microinverters, connection to battery storage is complex and requires extra components at a further cost (Cyanergy, n.d.).

9.2 Hybrid Solar Inverters

Hybrid solar inverters provide DC power to batteries for storage and AC power, typically required by fans (Cyanergy, n.d.). Subramaniam et al. (2020) point to the future scope for cascade H-bridge-based PV inverters, which implement control to minimize power interruption to the load or grid, potentially increasing the efficiency of solar dryers by providing more stable drying temperatures over an extended period.

10. CONTROL SYSTEMS

A control system uses devices to regulate processes in a system in response to inputs. In the case of a solar drying system, potential variables which may require control include temperature, air velocity, and humidity.

10.1 Temperature Control System

A temperature control system utilizes a temperature controller or thermostat, a sensor or thermocouple, and a programmable logic controller (PLC). The temperature desired (setpoint) is set using the temperature controller, which sends a signal to the PLC, which then implements the heating or cooling element depending on the input variation to the

setpoint (Sabale & Bute, 2020). Figure. 16 shows a block diagram of primary temperature control for a solar dryer.

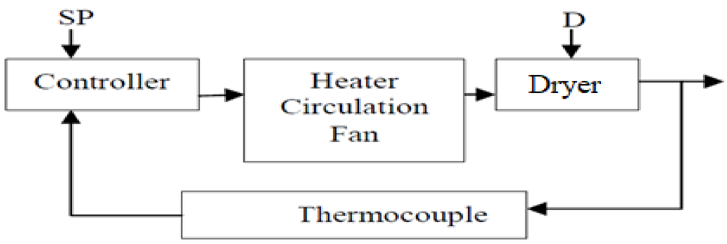


Figure 16: Block Diagram Showing Basic Temperature Control. Adapted from Rahman et al. (2013).

11. MODES OF HEAT TRANSFER

11.1 Conduction

Conduction is a mode of heat transfer wherein the energy processes occur at atomic and molecular activity levels. Heat is transferred where a temperature gradient is found, from high-energy particles to low-energy particles preceding a state of energy and temperature equilibrium reached by the elements. This is similar to osmosis transfer in biological membranes. Heat transfer by conduction is inevitably present in stationary objects with temperature gradients, and as such will be present in almost every system at some level and is governed by an equation with 'k' as thermal conductivity in W/m and L as the length in metres over which conduction occurs (Incropera et al., 2013).

11.2 Convection

Convection is the mode of heat transfer most influential in the functioning of a hybrid PV/T solar dryer and can be characterized as the heat transfer resultant from the bulk macroscopic motion of a fluid relative to another fluid or solid exhibiting a relative temperature gradient. The coefficient of heat transfer via convection is controllable to a large degree through the fluid material, fluid velocity, extended heat transfer area, and other variables of interest (Incropera et al., 2013).

11.3 Radiation

Radiation heat transfer results from the emission of heat energy through waves by a non-zero temperature mass. The study of the hybrid PV/T solar dryer largely focuses on photoelectric and thermal radiation emitted by the sun and captured by the PV cell and thermal collector system (Incropera et al., 2013).

12. INSULATION

12.1 Insulation Types

The Thermal Insulation Association of Southern Africa (2013), defines thermal insulation as a material that provides safety in "hot" working applications, reduces energy costs and heat loss, and maintains level-temperature conditions. Insulation types applicable to solar dryers include:

- Felt: a semi-flexible, fibrous material used to insulate tanks and heat exchangers.
- Spray fibre/foam: insulation used for irregular shapes usually made from polyurethane or polyisocyanurate.
- Foam board: rigid bound-fibre type insulation for flat surfaces used to insulate flat surfaces.
- Reflective insulation: insulation that provides a barrier for radiating heat.

Areas within a solar dryer requiring insulation to improve thermal performance include the solar collector, thermal storage unit, drying cabinet, and ducting. Osorio et al. (2017) combined transparent insulation materials (TIMs) with solar collectors, including a flat plate collector, parabolic trough collector, and a central receiver collector. Results showed that thermal losses decreased at high temperatures, increasing the efficiency of the solar collector. However, TIMs must have low thermal conductivity and emittances and high transmittance.

13. FOOD, HEALTH, AND SAFETY PRECAUTIONS

13.1 Safety Precautions

Caution is to be exercised when operating a hybrid PVT system while the solar drying chamber is in operation. Relevant safety precautions include the following:

- Vents/exhaust systems are not to be obstructed to prevent overheating of the system and the presence of excess humidity, which hinders performance.
- No individual should handle the drying chamber (reaching a high temperature of 60°C) while it is in operation without proper precautionary measures.
- The mesh tray material used in the drying chamber is to be food safe. Thus, 316 or 430 stainless is recommended for the drying trays (Marlin Steel, 2019) because such trays:
- Withstand high temperatures.
- Are resistant to acids, alkalis, and chlorides, which is imperative due to the liquid extraction from the drying product.
- Evade pitting corrosion when exposed to the salt present in food products.

14. CONCLUSIONS

Extensive literature research was conducted to realize solutions and designs for a hybrid PVT double-pass system. Solar drying using forced convection is effective by reducing the drying period compared to open sun drying, thus validating solar drying efficiency. The integrity of agricultural products such as maize, chilies, and mangoes is maintained. However, forced convection solar drying produces subminimum biltong. Solar thermal collectors such as ETC, tube, fin, and parabolic type collectors were explored to improve the thermal efficiency. ETC collectors can produce phenomenal energies but are expensive and there is poor accommodation for air as a fluid medium. Flat plate/tube type thermal collectors are not as efficient as fin-type and parabolic collectors, which produce optimal efficiencies in the form of a hybrid parabolic trough and finned collector. Latent, sensible, and the rmochemical heat storage systems utilize a PCM with a shell and tube heat exchanger which is effective, but it is costly. A cost-effective compromise uses sensible heat storage such as gravel, compounded with a parabolic reflector to optimize solar irradiation absorption. Monocrystalline/polycrystalline solar panels are recommended due to their efficiencies and properties. Thin-film solar panels are inadequate, despite being lightweight and reasonable. Monocrystalline panels are highly efficient but expensive, rendering polycrystalline panels as the more viable option. Lithium-ion batteries are a formidable electrochemical storage solution but remain expensive. An alternate battery solution is lead-acid batteries which are affordable and produce a smooth energy output. String, micro, and hybrid solar inverters are vital, as they convert DC current into AC current. A temperature control system comprising a thermostat, sensor, and PLC is necessary to regulate temperatures in the solar

drying system. The preceding research and experimentation analysis have provided insight into all domains of the hybrid PVT double-pass system. Unique improvements and alterations will be incorporated in the build of the project to construct an optimum design within project constraints.

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